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# Unique Transcriptome, Pathways, and Networks in the Human Endometrial Fibroblast Response to Progesterone in Endometriosis<sup>1</sup>

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## ABSTRACT

Eutopic endometrium in endometriosis has molecular evidence of resistance to progesterone ( $P_4$ ) and activation of the PKA pathway in the stromal compartment. To investigate global and temporal responses of eutopic endometrium to  $P_4$ , we compared early (6-h), intermediate (48-h), and late (14-Day) transcriptomes, signaling pathways, and networks of human endometrial stromal fibroblasts (hESF) from women with endometriosis (hESF<sub>endo</sub>) with hESF from women without endometriosis (hESF<sub>nonendo</sub>). Endometrial biopsy samples were obtained from subjects with and without mild peritoneal endometriosis ( $n = 4$  per group), and hESF were isolated and treated with  $P_4$  (1  $\mu$ M) plus estradiol ( $E_2$ ) (10 nM),  $E_2$  alone (10 nM), or vehicle for up to 14 days. Total RNA was subjected to microarray analysis using a Gene 1.0 ST (Affymetrix) platform and analyzed by using bioinformatic algorithms, and data were validated by quantitative real-time PCR and ELISA. Results revealed unique kinetic expression of specific genes and unique pathways, distinct biological and molecular processes, and signaling pathways and networks during the early, intermediate, and late responses to  $P_4$  in both hESF<sub>nonendo</sub> and hESF<sub>endo</sub>, although a blunted response to  $P_4$  was observed in the latter. The normal response of hESF to  $P_4$  involves a tightly regulated kinetic cascade involving key components in the  $P_4$  receptor and MAPK signaling pathways that results in inhibition of  $E_2$ -mediated proliferation and eventual differentiation to the decidual phenotype, but this was not established in the hESF<sub>endo</sub> early response to  $P_4$ . The abnormal response of this cell type to  $P_4$  may contribute to compromised embryonic implantation and infertility in women with endometriosis.

*decidualization, endometrial fibroblast, endometriosis, eutopic endometrium, progesterone, transcriptome*

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## INTRODUCTION

Endometriosis, a common gynecologic disorder, is characterized by endometrium-like tissue on the pelvic peritoneum, ovary, and rectovaginal septum. It is present in up to 60% of women with chronic pelvic pain and dysmenorrhea and up to 50% of women with infertility [1, 2]. Retrograde transplantation of steroid hormone-sensitive endometrial tissue and cells into the pelvic cavity at the time of menses is believed to account for peritoneal disease and is accompanied by a local inflammatory response that contributes to the observed pain and infertility [3]. This shed eutopic endometrium of women with endometriosis has different innate properties that likely contribute to its attachment to, invasion of, and growth on peritoneal structures, giving rise to the disorder in genetically, environmentally, and immunologically predisposed individuals [4, 5]. Eutopic endometrium is composed of several cell types that respond to the circulating steroid hormones estradiol ( $E_2$ ) and progesterone ( $P_4$ ) in preparation for blastocyst nidation, placentation, and sustainability of an established pregnancy. The human endometrial stromal fibroblast (hESF), in response to  $P_4$  after  $E_2$  priming, undergoes distinct morphological differentiation, with changes in the cytoskeleton and a functional transition from fibroblast-like to epithelium-like cells, which is accompanied by a unique biosynthetic and secretory phenotype, and plays a critical role in successful embryonic implantation [6]. When pregnancy ensues, the endometrial stromal compartment becomes uniformly “decidualized” and constitutes the decidua, a morphologically and functionally distinct tissue that persists throughout gestation and represents the maternal aspect of the maternal-fetal interface, composed of decidualized stromal fibroblasts, vascular elements, epithelium, and immune cells [7]. Through their responses to  $P_4$ , hESF communicate with the extracellular matrix, the invading trophoblast, and resident and peripheral leukocyte populations in the developing placental bed [8]. Thus, an abnormal hESF differentiation program can affect the success of implantation, early development, and pregnancy. In the setting of endometriosis, this differentiation program is compromised [4, 9].

hESF responses to  $P_4$  are complex and involve activation of PKA, the progesterone receptor (*PGR*) gene, and other pathways, with cross-talk between and among them [9–11], a consequence of  $P_4$  binding to its cognate nuclear receptors, and nongenomic mechanisms [12, 13]. Resistance to  $P_4$  actions in eutopic endometrium of women with endometriosis is believed to derive from lower levels of *PGRA*, *PGRB* [14, 15], and *PGR* coregulator expression [10], aberrant expression of specific transcription factors [16–18], and dysregulation of members and functions of specific pathways that drive hESF toward decidualization [4, 9, 19, 20]. We and others have demonstrated that hESF from women with endometriosis exhibit a blunted

TABLE 1. Subject characteristics for this study.

Patient	hESF used in experiments <sup>a</sup>	Diagnosis at laparoscopy	Age (yr)	Ethnicity
233 <sup>b</sup>	Microarray, ELISA, validation	Mild endometriosis, pelvic pain	31	Caucasian
243 <sup>b</sup>	Microarray, ELISA, validation	Minimal endometriosis, bilateral ovarian cyst, intramural myoma	46	Caucasian
267 <sup>b</sup>	Microarray, ELISA, validation	Mild endometriosis, pelvic pain	32	Caucasian
270	Microarray, ELISA, validation	Mild endometriosis, pelvic pain	49	Caucasian
236 <sup>b</sup>	Microarray, ELISA, validation	Symptomatic pelvic prolapse	47	Caucasian
310	Microarray, ELISA, validation	Intramural myoma, enterocele	41	Asian
316	Microarray, ELISA, validation	Intramural myoma, adenomyosis	42	Caucasian
326 <sup>b</sup>	Microarray, ELISA, validation	Intramural myoma	49	Asian

<sup>a</sup> ELISA, enzyme-linked immunoassay.

<sup>b</sup> hESF as used in the study by Giudice [8].

response to activation of the PKA pathway [9, 19]. However, it is unclear what the global response to  $P_4$  per se is in the impaired decidualization observed in hESF from women with endometriosis.

Thus, a comparative investigation of genes, gene families, and signaling and biological pathways involved in the hESF response to  $P_4$  in women with and without endometriosis is important to understand the mechanisms underlying normal and abnormal implantation and pregnancy maintenance. Herein, we compared early (6-h), intermediate (48-h), and late (14-Day) in vitro whole-genome responses of hESF from women with endometriosis (hESF<sub>endo</sub>) to hESF from women without endometriosis (hESF<sub>nonendo</sub>) treated with  $P_4$  plus  $E_2$  ( $E_2P_4$ ), or  $E_2$  alone, or vehicle alone. Using this experimental paradigm, the data demonstrate unique phenotypes, gene expression processes, biochemical and signaling pathways, and networks suggestive of early, intermediate, and late responses of hESF<sub>nonendo</sub> and hESF<sub>endo</sub> to  $P_4$ , giving insights into the complexity of events occurring normally in response to  $P_4$  and in the setting of endometriosis.

## MATERIALS AND METHODS

### Tissues and Cells

Endometrial tissue samples were obtained in accordance with the guidelines of the Declaration of Helsinki. Written, informed consent was obtained from all subjects. The study was approved by the Committee on Human Research of the University of California San Francisco (UCSF) and the Stanford University Committee on the Use of Human Subjects in Medical Research. Some samples were also obtained from the National Institutes of Health Specialized Cooperative Centers Program in Reproduction and Infertility Research (SCPRR) Human Endometrial Tissue and DNA Bank at UCSF. Control

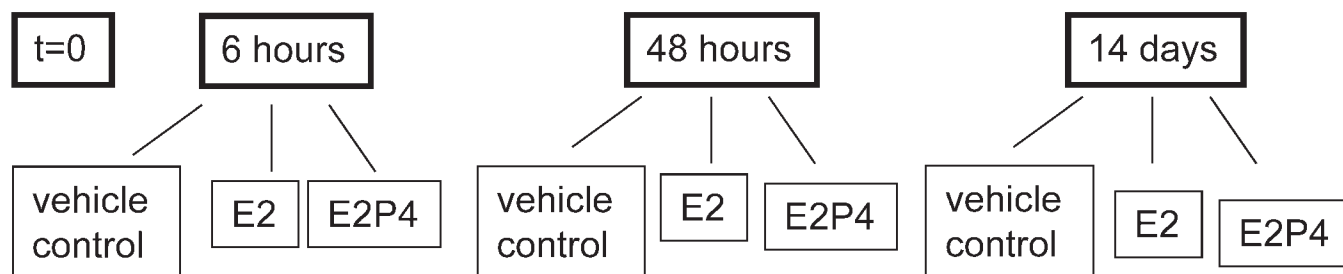
subjects were premenopausal women ( $44.75 \pm 1.7$  years old; range 41–49 years old) undergoing hysterectomy for benign conditions (Table 1), with regular menstrual cycles (25–35 days), surgically confirmed absence of endometriosis, and no history of endometriosis. Endometriosis subjects were  $39.5 \pm 4.2$ -year-old (range, 31–49 years old;  $P = 0.35$ , vs. hESF<sub>nonendo</sub> subjects) women with regular menstrual cycles, in whom minimal to mild peritoneal endometriosis was diagnosed by visualization of pelvic lesions during laparoscopy and histologic evaluation (Table 1). Endometriosis was staged according to the revised American Fertility Society classification system [21]. All subjects were documented not to be pregnant and not to have had hormonal treatment for at least 3 months before surgery.

Endometrial tissue was digested with collagenase, and hESF were isolated and plated with Dulbecco modified Eagle medium (DMEM)/molecular cell developmental biology 105 (MCDB-105) medium with 10% charcoal-stripped fetal bovine serum (FBS), insulin (5 mg/ml), gentamicin, penicillin, and streptomycin, as described previously [22, 23]. All cells used were at Passage 2. Subsequently, hESF were plated in 6-cm plastic dishes, and, after they reached confluency, medium was changed to a low-serum medium (LSM; i.e., DMEM/MCDB-105 medium containing ascorbic acid, transferrin, and gentamicin with 2% FBS) for 24 h prior to treatment. The concentration of FBS (2%) in the culture medium was determined by culturing two preparations in triplicate for up to 16 days with  $1 \mu\text{M } P_4$  plus 10 nM  $E_2$  ( $E_2P_4$ ) in 0%, 0.5%, 1%, 2%, 5%, and 10% FBS, and the classical decidual marker IGFBP1, in conditioned medium (CM) was measured by ELISA (Diagnostic Systems Labs, Webster, TX). Optimal IGFBP1 secretion was observed in the culture with 2% FBS (data not shown).

### Hormonal Treatment, RNA Isolation, and Processing for Microarray Analysis

Figure 1 shows the experimental design of the present study. Duplicate cultures of hESF in LSM were treated with  $E_2P_4$  or with 10 nM  $E_2$  alone ( $E_2$ ) or with vehicle (vehicle control), and cells and CM were collected at time ( $t$ ) of 0 h, 6 h (early response), 48 h (intermediate response), and 14 days (late response), and CM was changed every 2 days. Total RNA was isolated from

## Treatment groups of hESF<sub>nonendo</sub> and hESF<sub>endo</sub>



*N=4, in duplicate*

FIG. 1. Experimental design. Treatment groups were similar for hESF<sub>nonendo</sub> and hESF<sub>endo</sub>. For analysis of microarray and QRT-PCR data, all groups were normalized to  $t=0$ , and then the normalization was conducted within each time-group:  $E_2P_4$  was normalized to  $E_2$ , which was normalized to the vehicle control, with the resulting data reflecting the pure  $P_4$  response.

TABLE 2. Primer sequences used in real-time RT-PCR experiments.

Gene	Sense primer 5'–3'	Antisense primer 5'–3'
<i>IGFBP1</i>	CTATGATGGCTCGAAGGCTC	TTCTTGTTCAGTTTGGCAG
<i>PRL</i>	CATCAACAGCTGCCACACTT	CGTTTGGTTTGCTCCTCAAT
<i>GPX3</i>	AGCCGGGGACAAGAGAAGT	CCAGAATGACCAGACCGAAT
<i>SLC7A8</i>	ACCGAAACAACACCGAAAAG	GATTCAGAGCCGATGATGT
<i>IMPA2</i>	TGGGAGGAGTGCTTCCAG	GCCTCTTCTGCAATGAACCT
<i>CNR1</i>	AAGACCCTGGTCTGATCCT	CGCAGTCTTACTCTCTCAG
<i>SPARCL1</i>	GGATGAAAAGAGGCTTTTGG	TCAAAGAAACGGGTTATGCAG
<i>EGFR</i>	GAATGCATTTGCCAAGTCCT	CGTCTATGCTGCTCCTCAGTCA
<i>DKK1</i>	CATCAGACTGTGCCTCAGGA	CCACAGTAACAACGCTGGAA
<i>ERRF1 (MIG6)</i>	TTGCTGCTCAGGAGATCAGA	TTCAGACTGTAGGCCATGGTT
<i>RPL19</i>	CGAGATAATGGGAGGAGCC	GCCCATCTTTGATGAGCTTC

individual plates and purified using an RNeasy mini-kit (Qiagen, Valencia, CA) following the manufacturer's protocol. Samples were stored in RNase-free H<sub>2</sub>O, purity was analyzed by the A<sub>260</sub>:A<sub>280</sub> nm ratio, and RNA quality and integrity were assessed by using a Bioanalyzer 2100 unit (Agilent Technologies, Santa Clara, CA). All samples had high-quality RNA (RNA integrity number [RIN] = 9.7–10).

Duplicate RNA preparations were pooled and prepared according to the manufacturer's microarray preparation protocol (Affymetrix, Inc., Santa Clara, CA) as described previously [9]. Briefly, for each sample, 100 ng of total RNA was reverse-transcribed to cDNA by using 500 ng of T7-(N6) primer and SuperScript II. A second strand of DNA was generated using DNA polymerase, followed by overnight in vitro transcription to generate cRNA. After samples were processed through cRNA clean-up spin columns (Affymetrix), 10 µg of cRNA was reverse-transcribed using random primers and SuperScript II. Mixtures were digested with RNase H, and cDNA was purified by cDNA clean-up spin columns (Affymetrix). Finally, 5.5 µg of sense cDNA was fragmented and labeled using a GeneChip WT-terminal labeling kit. The quality of the cDNA and the fragmented cDNA was assessed with an Agilent bioanalyzer. Individual samples were hybridized to Human Gene 1.0 ST arrays (Affymetrix) containing 19 492 genes. Data were scanned according to the protocol described in the WT sense target-labeling assay manual from Affymetrix (version 4; product code FS450\_0007).

### Microarray Gene Expression Data Analysis

The intensity values of different probe sets (genes) in the GeneChip operating software (Affymetrix) were imported into GeneSpring GX version 10.0 software (Agilent Technologies, Santa Clara, CA) and processed using the robust multiarray analysis algorithm for background adjustment, normalization, and log<sub>2</sub> transformation of perfect-match values [9, 24]. The data at each time point were normalized to the corresponding sample at  $t = 0$  h. Then, the normalization was conducted within each time-group: data from E<sub>2</sub>P<sub>4</sub>-treated samples were normalized to those from E<sub>2</sub>-treated samples, which were normalized to the vehicle control, with the resulting data thus reflecting the specific temporal response to P<sub>4</sub>. We performed three major comparisons of the response to P<sub>4</sub>: within the nonendometriosis group, within the endometriosis group, and between hESF<sub>endo</sub> and hESF<sub>nonendo</sub>. The resulting gene lists generated included only genes showing >1.5-fold change in expression and a  $P$  value of <0.05 by using a two-way ANOVA parametric test and Benjamini-Hochberg multiple testing correction for false discovery rate.

### Principal Component Analysis and Hierarchical Clustering

Principal component analysis (PCA) and hierarchical clustering were performed as described previously [9, 24]. We applied the unbiased PCA algorithm in GeneSpring software to all samples, using all 19 492 genes on the Human Gene 1.0 ST array chip to look for similar expression patterns and underlying cluster structures. Hierarchical cluster analysis uses only differentially expressed genes from all samples and from among all experimental conditions and was conducted using the smooth-correlation-distance-measure algorithm (GeneSpring) to identify samples with similar patterns of gene expression.

### Gene Ontology and Pathway Analyses

Gene ontology and functional annotations were carried out using Ingenuity Pathway analysis (IPA) (Ingenuity Systems, Redwood City, CA), into which gene symbols and fold changes of up- and downregulated genes in each pairwise comparison were imported [9].

### Microarray Validation by Real-Time PCR

Genes showing >1.5-fold up- or downregulation at each time point were randomly chosen for validation by quantitative real-time PCR (QRT-PCR). QRT-PCR assays were performed in duplicate using SYBR Green PCR Master Mix (Bio-Rad Laboratories, Hercules, CA) according to the manufacturer's instructions. The *RPL19* housekeeping gene was used as the normalizer. Primer sequences (Table 2) were designed from public databases, and PCR assays were run using Mx4000 and Mx3005 QPCR systems (Stratagene, La Jolla, CA) under thermal cycling conditions as described previously [9, 22]. Pair-wise comparisons between treatments and control at each time point were performed. All validation experiments used four-subject samples in each group. Statistical analysis for the QRT-PCR assays was performed using the nonparametric Mann-Whitney  $U$ -test. Significance was determined at a  $P$  value of  $\leq 0.05$ .

### ELISA

ELISAs were carried out to quantify IGFBP1 (Alpha Diagnostic International, San Antonio, TX), PRL (Diagnostic Systems Labs, Webster, TX), and amphiregulin (AREG) and HBEGF (both, R&D Systems Inc., Minneapolis, MN) levels in CM from cultured hESF, performed according to manufacturers' instructions. All samples were assayed in duplicate, and values were plotted against a standard curve. Levels of IGFBP1, PRL, AREG, and HBEGF expression in CM for each sample were normalized to total RNA. The IGFBP1 ELISA kit had inter- and intra-assay coefficient of variation values (CV) of 5%–7.4% and 2.4%–3.4%, respectively, and the PRL ELISA inter- and intra-assay CVs were 6.7%–10.4% and 7.8%–8.2%, respectively. The sensitivity for the AREG ELISA was 15 pg/ml, with a linear range up to 1000 pg/ml. The sensitivity for the HBEGF ELISA was 30 pg/ml, with a linear range up to 2000 pg/ml. Statistical analysis of the ELISA data was performed using a two-tailed type 3 Student- $t$  test.

## RESULTS

### PCA and Hierarchical Clustering Analysis

PCA distributes samples into a three-dimensional space based on variations in gene expression, with samples that have similar gene expression profile trends clustering close together. When we used all genes on the Affymetrix array and a completely unbiased approach, the samples roughly clustered into two major groups, in a comparison of disease versus no disease (Fig. 2A).

Unsupervised hierarchical clustering analyses based on the combined gene list derived from pair-wise comparisons as described above (Fig. 1) at each time point resulted in a dendrogram of sample clustering and a heat map of gene expression (Fig. 2B) in which all control samples ( $t = 0$  h and vehicle control) and all treated samples fell into two main branches. Short-term treatment (6-h) groups (vehicle control, E<sub>2</sub>-treated, and E<sub>2</sub>P<sub>4</sub>-treated) clustered together in one sub-branch with  $t = 0$ . Intermediate (48-h) and long-term (14-Day) treatment groups clustered into other main sub-branches; the latter group clustered further into two sub-branches, based on the disease state, followed by further

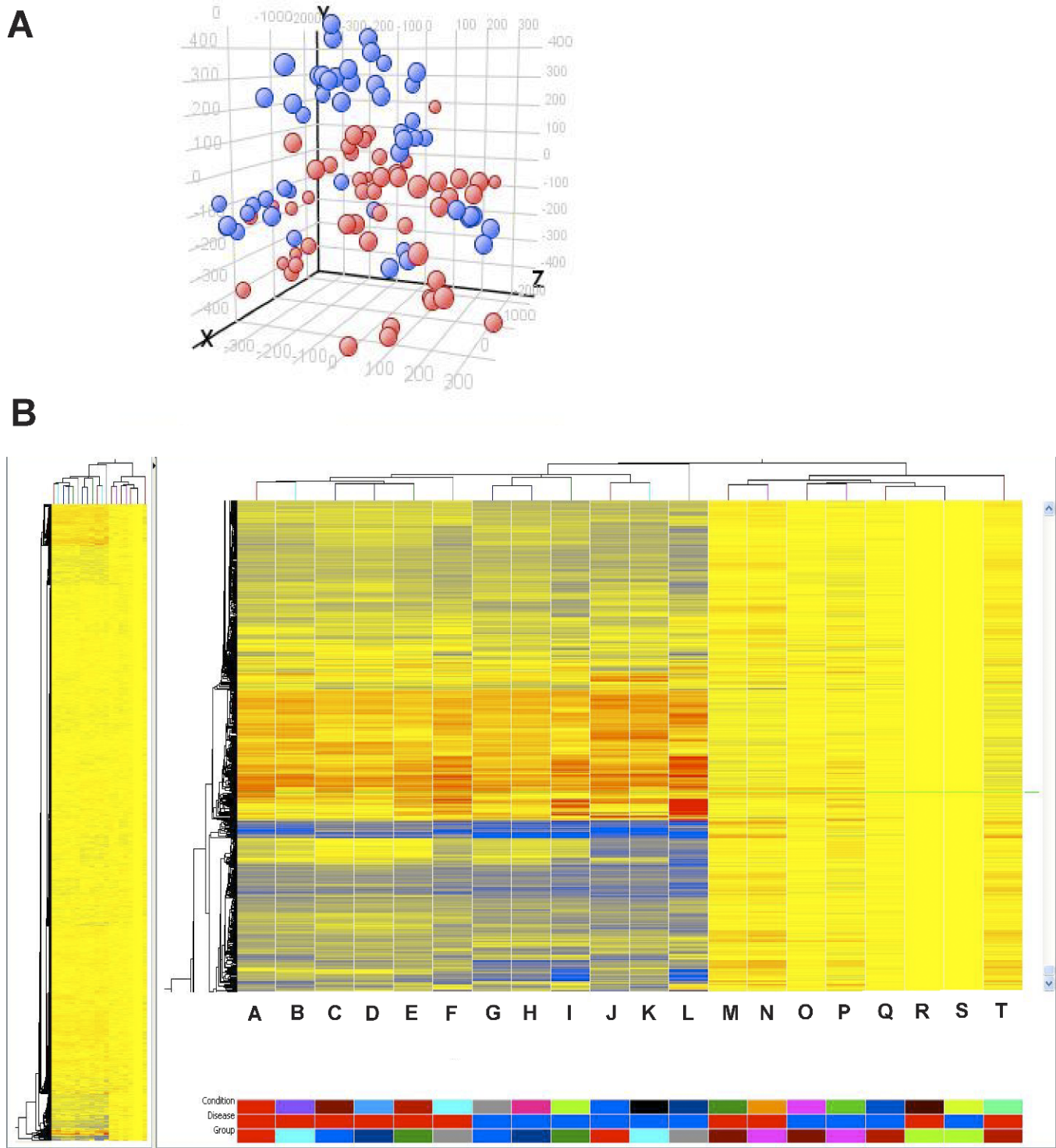


FIG. 2. Clustering and cluster trees. **A**) Principal component analysis of  $hESF_{nonendo}$  and  $hESF_{endo}$  at  $t = 0, 6,$  and  $48$  h and at  $14$  days, treated with or without  $E_2$  and  $P_4$ . PCA was applied to all samples that were characterized by the gene expression of all probes on a Gene 1.0 ST platform. Blue, no endometriosis samples; red, endometriosis samples. **B**) Hierarchical clustering analysis of  $hESF_{nonendo}$  and  $hESF_{endo}$  at  $t = 0, 6,$  and  $48$  h and at  $14$  days, treated with or without (control [c]) estrogen ( $E_2$ ) and progesterone ( $P_4$ ), using only the profiles of significantly regulated genes. The heat map represents relative expression levels of genes in the  $hESF$  samples: each horizontal line represents a single gene, and each column represents a single sample. The relative expression of each gene is color coded as high (red) or low (blue) or no change (yellow). Groups: A,  $E_2$  14-Day endo; B, c 14-Day endo; C,  $E_2$  48-h endo; D, c 48-h endo; E,  $E_2P_4$  48-h endo; F,  $E_2P_4$  14-Day endo; G,  $E_2$  48-h nonendo; H, c 48-h nonendo; I,  $E_2P_4$  48-h nonendo; J,  $E_2$  14-Day nonendo; K, c 14-Day nonendo; L,  $E_2P_4$  14-h nonendo; M,  $E_2$  6-h endo; N,  $E_2P_4$  6-h endo; O,  $E_2$  6-h nonendo; P,  $E_2P_4$  6-h nonendo; Q, c 6-h nonendo; R,  $t = 0$  endo; S,  $t = 0$  nonendo; T, c 6-h endo.

TABLE 3. List of up- and downregulated genes (BH corrected  $P$  value < 0.05) in comparison of hESF<sub>endo</sub> at  $t=0$  (hESF<sub>endo</sub>  $t=0$ ) versus hESF<sub>nonendo</sub> at  $t=0$ , expressed as fold change (FC).

Gene symbol	FC ([endometriosis-t0] vs. [nonendometriosis-t0])	Gene description
CNIH3	2.35	Cornichon homolog 3 (Drosophila)
ANKRD1	2.14	Ankyrin repeat domain 1 (cardiac muscle)
AREG	2.12	Amphiregulin (schwannoma-derived growth factor)
TGFB2	1.81	Transforming growth factor, beta 2
CLDN1	1.79	Claudin 1
HBEGF	1.71	Heparin-binding EGF-like growth factor
ITGA2	1.67	Integrin, alpha 2 (CD49B, alpha 2 subunit of VLA-2 receptor)
NEDD4L	1.61	Neural precursor cell expressed, developmentally down-regulated 4-like
HS3ST3B1	1.58	Heparan sulfate (glucosamine) 3-O-sulfotransferase 3B1
SLC20A1	1.58	Solute carrier family 20 (phosphate transporter), member 1
ANKH	1.57	Ankylosis, progressive homolog (mouse)
STC2	1.57	Stanniocalcin 2
RGS4	1.56	Regulator of G-protein signaling 4
TM7SF4	1.55	Transmembrane 7 superfamily member 4
UNQ1940	1.55	HWKM1940
SLC16A6	1.50	Solute carrier family 16, member 6 (monocarboxylic acid transporter 7)
FKBP5 LOC285847	-1.50	FK506 binding protein 5   hypothetical protein LOC285847
C10orf10	-1.50	Chromosome 10 open reading frame 10
CCNE2	-1.50	Cyclin E2
SEPP1	-1.50	Selenoprotein P, plasma, 1
SULF2	-1.51	Sulfatase 2
C4orf31	-1.52	Chromosome 4 open reading frame 31
IL1R1	-1.54	Interleukin 1 receptor, type 1
OSR2	-1.54	Odd-skipped related 2 (Drosophila)
ARHGAP28	-1.54	Rho GTPase activating protein 28
TMEM16D	-1.55	Transmembrane protein 16D
RASL11A	-1.55	RAS-like, family 11, member A
CYB5A	-1.55	Cytochrome b5 type A (microsomal)
MYLIP	-1.56	Myosin regulatory light chain interacting protein
FMO2	-1.57	Flavin containing monooxygenase 2 (non-functional)
LRRK2	-1.57	Leucine-rich repeat kinase 2
ACTA2	-1.58	Actin, alpha 2, smooth muscle, aorta
KGFLP1 KGFLP2 LOC100126582  FGF7P2 FLJ20444 LOC100132771  LOC100133691	-1.58	Keratinocyte growth factor-like protein 1   keratinocyte growth factor-like protein 2
METTL7A	-1.59	Methyltransferase like 7A
KGFLP2 KGFLP1 FGF7P2 FLJ20444  LOC100132771 LOC100133691	-1.60	Keratinocyte growth factor-like protein 2   keratinocyte growth factor-like protein 1
UST	-1.61	Uronyl-2-sulfotransferase
CD226	-1.62	CD226 molecule
LMOD1	-1.62	Leiomodin 1 (smooth muscle)
RORB	-1.64	RAR-related orphan receptor B
ABI3BP	-1.64	ABI gene family, member 3 (NESH) binding protein
PRLR	-1.67	Prolactin receptor
ABCC9	-1.67	ATP-binding cassette, sub-family C (CFTR/MRP), member 9
IFIT1	-1.68	Interferon-induced protein with tetratricopeptide repeats 1
TACSTD2	-1.68	Tumor-associated calcium signal transducer 2
ITGB8	-1.75	Integrin, beta 8
PGR	-1.76	Progesterone receptor
ENPP1	-1.76	Ectonucleotide pyrophosphatase/phosphodiesterase 1
RASGRP1	-1.87	RAS guanyl releasing protein 1 (calcium and DAG-regulated)
TNC	-1.89	Tenascin C (hexabrachion)
SMPDL3A	-1.90	Sphingomyelin phosphodiesterase, acid-like 3A
SLC40A1	-1.94	Solute carrier family 40 (iron-regulated transporter), member 1
C1R	-1.99	Complement component 1, r subcomponent
CPM	-2.04	Carboxypeptidase M
IL7R	-2.11	Interleukin 7 receptor
PLXNC1	-2.11	Plexin C1
NEFM	-2.21	Neurofilament, medium polypeptide 150kDa
FBLN1	-2.30	Fibulin 1

branching according to the treatment time (Fig. 2B). This clustering demonstrates that cultured, treated hESF cluster according to the duration of hormonal exposure, similar to in vivo hormonal exposure of whole-tissue samples, which cluster based primarily on cycle phase [24, 25] and thereafter based on disease state [25].

#### *Differences in Gene Expression Between hESF<sub>endo</sub> and hESF<sub>nonendo</sub> at $t=0$*

Comparisons between gene expression in hESF<sub>endo</sub> and hESF<sub>nonendo</sub> at  $t=0$  (untreated uncultured control) revealed differences between the two (Table 3). In particular, we observed upregulation of members of the *EGF* and *TGFB*

families (*HBEGF*, *AREG*, *TGFB2*), the *SLC16A6* solute carrier, and the neural precursor cell expressed developmentally downregulated 4-like (*NEDD4L*) gene in hESF<sub>endo</sub> compared with the hESF<sub>nonendo</sub> samples. Also, there was significant downregulation of several genes at  $t = 0$  in hESF<sub>endo</sub> versus hESF<sub>nonendo</sub>, including the *FKBP5*, *ILIR1*, sulfatase 2, prolactin receptor, methyltransferase-like 7A, and plexin C1 genes; the cytoskeletal *MYLIP* and *ACTA2* genes; and the progesterone receptor (*PGR* [1.75-fold]) gene (Table 3). IPA analysis of the comparison of these groups showed that the *HBEGF* and *AREG* genes were allocated to several different signaling pathways, including neuregulin signaling, ERBB2 (HER-2) signaling in breast cancer, pancreatic adenocarcinoma signaling, and others. Analysis of hESF transcriptomes at  $t = 0$  revealed no gene profile was unique to one menstrual cycle phase versus another (data not shown), consistent with previous reports [22].

#### Early, Intermediate, and Late Responses to P<sub>4</sub>

We investigated the temporal responses presumably to P<sub>4</sub> (by comparison of E<sub>2</sub>P<sub>4</sub> vs. E<sub>2</sub> response) of hESF<sub>nonendo</sub> and hESF<sub>endo</sub> and then compared the two responses to each other. These comparisons enabled us to define the “normal” P<sub>4</sub>-regulated program from early response genes to the full decidual phenotype, as well as the hESF<sub>endo</sub> response.

#### Early Response

*hESF<sub>nonendo</sub>*. In a comparison of hESF<sub>nonendo</sub> treated with E<sub>2</sub>P<sub>4</sub> versus E<sub>2</sub> alone, upregulated genes included the *SLC7A8* solute carrier, the *PGR* *FKBP5* chaperone, the *SPARCL1* gene, the ERBB receptor feedback inhibitor 1 (*ERRF1*, *MIG6*), *IMPA2*, and *GCNT1* genes, the adrenergic alpha-2C receptor, and chromosome 10 open reading frame 10 (*C10orf10*), among others (Table 4). There were no significantly downregulated genes at the 1.5-fold change cutoff.

*hESF<sub>endo</sub>*. Analysis of microarray data of gene expression after 6 h of treatment in hESF<sub>endo</sub> revealed no genes were up- or downregulated at the >1.5-fold cutoff ( $P < 0.05$ ) (Table 4). Interestingly, in the E<sub>2</sub>-treated groups, the E<sub>2</sub> target *PGR* gene was upregulated in hESF<sub>nonendo</sub> at 6 h, demonstrating early responsiveness to E<sub>2</sub>; however, in hESF<sub>endo</sub>, there was delayed *PGR* upregulation, first noted at 48 h of E<sub>2</sub> treatment (data not shown). This time shift in E<sub>2</sub> regulation of the *PGR* gene may account for the relative resistance to P<sub>4</sub> observed in hESF<sub>endo</sub> at the 6-h time point of cells treated with E<sub>2</sub>P<sub>4</sub>. Importantly, the early response to P<sub>4</sub> (E<sub>2</sub>P<sub>4</sub> vs. E<sub>2</sub>) signaling involving the *PGR* chaperone and the MAPK pathway was not established in hESF<sub>endo</sub>.

#### Intermediate Response

*hESF<sub>nonendo</sub>*. In a comparison of E<sub>2</sub>P<sub>4</sub>- and E<sub>2</sub>-treated hESF<sub>nonendo</sub> at 48 h, in addition to the sustained or enhanced upregulation of the early response genes already described above at 6 h, the first upregulation was observed for the *IGF1*, *DKK1*, *KLF6*, *MAOB*, *ILIR1*, ectonucleotide pyrophosphatase/phosphodiesterase 1 (*ENPP1*) (regulator of extracellular inorganic pyrophosphate [PPi]), sulfatase 2, plexin C1, and osteomodulin genes and others (Table 4). Among the downregulated were the *SLC16A6* soluble carrier, the *MMP11*, and the dual-specificity phosphatase 6 genes and others (Table 4).

*hESF<sub>endo</sub>*. In hESF<sub>endo</sub>, there were only three significantly upregulated genes: the *IMPA2* (upregulated in hESF<sub>nonendo</sub> at 6 h), methyltransferase-like 7A, and *ILIR1* genes (Table 4).

#### Late Response

*hESF<sub>nonendo</sub>*. After hESF<sub>nonendo</sub> was treated for 14 days, in addition to the continued or enhanced expression of the genes mentioned above, the uniquely upregulated (>1.5-fold,  $P < 0.05$ ) group included the classical P<sub>4</sub>-regulated *PRL*, *IGFBP1*, *GPX3*, *MAOA*, tenascin family, prolactin receptor, parathyroid hormone-like hormone, adenylate cyclase 1, hydroxysteroid (17-beta) dehydrogenase type 11 (*HSD17B11*), and *FOXO1A* genes and others (Table 5). Among those newly observed and significantly downregulated were the *IGFBP5*, cyclin D1, neurofilament medium polypeptide (*NEFM*), and pleiotrophin (*PTN*, heparin-binding growth factor 8, neurite growth-promoting factor 1) genes and others (Table 5).

*hESF<sub>endo</sub>*. In contrast, in hESF<sub>endo</sub>, only a few P<sub>4</sub>-dependent genes were (up)regulated, including the *C10orf10*, *SLC7A8* (both upregulated at 6 h in hESF<sub>nonendo</sub>), *ADH1B* (upregulated at 48 h in hESF<sub>nonendo</sub>), and *ILIR1* genes (Table 5).

#### Validation of Microarray Data by RT-PCR

To validate microarray data by QRT-PCR, we randomly selected nine genes from the microarray data analysis: *IGFBP1*, *PRL*, *IMPA2*, *SLC7A8*, *DKK1*, *GPX3*, *ERRF1* (*MIG6*), *SPARCL1*, and *CNRI* (Fig. 3). There was very high concordance of gene regulation observed in the microarray analysis and the validation studies. We confirmed significant dysregulation of P<sub>4</sub>-regulated endometrial genes, such as *IGFBP1*, *IMPA2*, *SLC7A8*, *GPX3*, *ERRF1*, *SPARCL1*, and *CNRI*, in hESF<sub>endo</sub> compared to those in hESF<sub>nonendo</sub> in response to E<sub>2</sub>P<sub>4</sub> versus E<sub>2</sub> treatment, even at earlier time points (Fig. 3).

#### Validation of Microarray Data by ELISA

*IGFBP1* and *PRL*. Secretion of the IGFBP1 decidualization marker, but not PRL, in response to E<sub>2</sub>P<sub>4</sub> versus E<sub>2</sub> treatment differed between hESF<sub>endo</sub> and hESF<sub>nonendo</sub> (Fig. 4), confirming the mRNA validation data (Fig. 3).

*Amphiregulin and heparin-binding EGF-like growth factor secretion by hESF*. Previous publications have implicated the EGF signaling network in the pathogenesis of endometriosis [25, 26]. Because amphiregulin (*AREG*) and heparin-binding EGF-like growth factor (*HBEGF*) transcripts were upregulated in hESF<sub>endo</sub> versus hESF<sub>nonendo</sub> at  $t = 0$  and at 6 h (Table 3, Supplemental Table S1 [available online at [www.biolreprod.org](http://www.biolreprod.org)]), we measured AREG and HBEGF protein in CM of hESF. No detectable AREG protein was found in CM from hESF<sub>nonendo</sub> at any time point or from any treatment group. However, all hESF<sub>endo</sub> secreted AREG (data not shown). There was a tendency toward increased AREG expression with time; however, differences from one time point to another were not significant, and there was no apparent effect of hormonal treatment on AREG levels in CM (data not shown), suggesting constitutive expression of this growth factor in hESF<sub>endo</sub>. There was no HBEGF protein detected in CM from hormonally treated and control hESF<sub>nonendo</sub> at different time points, and hESF<sub>endo</sub> secretion levels of HBEGF in CM were at the lower limit of detection of the assay (data not shown).

#### Early and Late Responses in hESF<sub>endo</sub> Versus hESF<sub>nonendo</sub>: Canonical Pathways and Networks

The degree of regulation of signaling pathways and network formations in different comparison groups depends on the total number of genes regulated in each group (see gene lists in

TABLE 4. List of regulated genes (BH corrected  $P$  value < 0.05) in comparison of hESF<sub>nonendo</sub> or hESF<sub>endo</sub> treated with E<sub>2</sub>P<sub>4</sub> for 6-h (EP6) or 48-h (EP48) versus hESF<sub>nonendo</sub> or hESF<sub>endo</sub> treated with E<sub>2</sub> for 6-h (E6) or 48-h (E48), expressed as fold change (FC).<sup>a</sup>

Gene symbol	FC	Gene description
<b>hESF<sub>nonendo</sub> EP6 vs. hESF<sub>nonendo</sub> E6</b>		
<i>FKBP5 LOC285847</i>	1.99	FK506 binding protein 5   hypothetical protein LOC285847
<i>IMPA2</i>	1.67	Inositol(myo)-1(or 4)-monophosphatase 2
<i>SLC7A8</i>	1.67	Solute carrier family 7 (cationic amino acid transporter, y+ system), member 8
<i>ERRF1</i>	1.61	ERBB receptor feedback inhibitor 1
<i>GCNT1</i>	1.56	Glucosaminyl (N-acetyl) transferase 1, core 2 (beta-1,6-N-acetylglucosaminyltransferase)
<i>SPARCL1</i>	1.56	SPARC-like 1 (mast9, hev1n)
<i>C10orf10</i>	1.54	Chromosome 10 open reading frame 10
<i>ADRA2C</i>	1.51	Adrenergic, alpha-2C-, receptor
<b>hESF<sub>nonendo</sub> EP48 vs. hESF<sub>nonendo</sub> E48</b>		
<i>P2RY14</i>	3.37	Purinergic receptor P2Y, G-protein coupled, 14
<i>IGF1</i>	3.11	Insulin-like growth factor 1 (somatomedin C)
<i>ENPP1</i>	2.98	Ectonucleotide pyrophosphatase/phosphodiesterase 1
<i>FKBP5 LOC285847</i>	2.98	FK506 binding protein 5   hypothetical protein LOC285847
<i>MYOCD</i>	2.97	Myocardin
<i>IMPA2</i>	2.95	Inositol(myo)-1(or 4)-monophosphatase 2
<i>ADH1B</i>	2.86	Alcohol dehydrogenase 1B (class I), beta polypeptide
<i>RORB</i>	2.67	RAR-related orphan receptor B
<i>ADRA2C</i>	2.21	Adrenergic, alpha-2C-, receptor
<i>ABI3BP</i>	2.18	ABI gene family, member 3 (NESH) binding protein
<i>MOBK2L2</i>	2.15	MOB1, Mps One Binder kinase activator-like 2B (yeast)
<i>SPARCL1</i>	2.14	SPARC-like 1 (mast9, hev1n)
<i>SLC7A8</i>	2.05	Solute carrier family 7 (cationic amino acid transporter, y+ system), member 8
<i>IL1R1</i>	2.02	Interleukin 1 receptor, type I
<i>METTL7A</i>	2.00	Methyltransferase like 7A
<i>ACSL1</i>	1.95	Acyl-CoA synthetase long-chain family member 1
<i>LASS6</i>	1.93	LAG1 homolog, ceramide synthase 6
<i>CRISPLD2</i>	1.91	Cysteine-rich secretory protein LCCL domain containing 2
<i>ERRF1</i>	1.91	ERBB receptor feedback inhibitor 1
<i>ADAMTS1</i>	1.88	ADAM metalloproteinase with thrombospondin type 1 motif, 1
<i>SERPINE1</i>	1.88	Serpin peptidase inhibitor, clade E (nexin, plasminogen activator inhibitor type 1), member 1
<i>APCDD1</i>	1.87	Adenomatous polyposis coli down-regulated 1
<i>C10orf10</i>	1.86	Chromosome 10 open reading frame 10
<i>MUM1L1</i>	1.84	Melanoma associated antigen (mutated) 1-like 1
<i>ZBTB16</i>	1.83	Zinc finger and BTB domain containing 16
<i>NBLA00301</i>	1.80	Nbla00301
<i>NLGN4X</i>	1.77	Neuroigin 4, X-linked
<i>ABCC9</i>	1.76	ATP-binding cassette, sub-family C (CFTR/MRP), member 9
<i>TSC22D3</i>	1.74	TSC22 domain family, member 3
<i>CCDC102B</i>	1.73	Coiled-coil domain containing 102B
<i>ADH1C</i>	1.73	Alcohol dehydrogenase 1C (class I), gamma polypeptide
<i>SORBS1</i>	1.71	Sorbin and SH3 domain containing 1
<i>PPAP2B</i>	1.64	Phosphatidic acid phosphatase type 2B
<i>OMD</i>	1.63	Osteomodulin
<i>OSR2</i>	1.61	Odd-skipped related 2 (Drosophila)
<i>TLR4</i>	1.60	Toll-like receptor 4
<i>PLXNC1</i>	1.58	Plexin C1
<i>HAND2</i>	1.56	Heart and neural crest derivatives expressed 2
<i>DKK1</i>	1.56	Dickkopf homolog 1 ( <i>Xenopus laevis</i> )
<i>MAOB</i>	1.55	Monoamine oxidase B
<i>C5orf23</i>	1.55	Chromosome 5 open reading frame 23
<i>NPR3</i>	1.54	Natriuretic peptide receptor C/guanylate cyclase C (atriatriuretic peptide receptor C)
<i>KLF6</i>	1.53	Kruppel-like factor 6
<i>SYTL4</i>	1.53	Synaptotagmin-like 4 (granuphilin-a)
<i>SULF2</i>	1.52	Sulfatase 2
<i>RHOU</i>	1.52	Ras homolog gene family, member U
<i>ZEB1</i>	1.50	Zinc finger E-box binding homeobox 1
<i>SLC16A6</i>	-1.50	Solute carrier family 16, member 6 (monocarboxylic acid transporter 7)
<i>AFAP1L2</i>	-1.53	Actin filament associated protein 1-like 2
<i>MMP11</i>	-1.59	Matrix metalloproteinase 11 (stromelysin 3)
<i>CCRL1</i>	-1.60	Chemokine (C-C motif) receptor-like 1
<i>FJX1</i>	-1.61	Four jointed box 1 (Drosophila)
<i>KRT34</i>	-1.61	Keratin 34
<i>FRY</i>	-1.62	Furry homolog (Drosophila)
<i>KRTAP14 LOC728952 LOC730743</i>	-1.63	Similar to keratin associated protein 1-1   hypothetical LOC728952
<i>LOXL4</i>	-1.69	Lysyl oxidase-like 4
<i>STC1</i>	-1.71	Stanniocalcin 1
<i>GBP4</i>	-1.76	Guanylate binding protein 4
<i>RG54</i>	-1.78	Regulator of G-protein signaling 4
<i>KRTAP1-5 LOC728956</i>	-1.92	Keratin associated protein 1-5   hypothetical LOC728956
<i>KRTAP1-5 LOC728956</i>	-1.92	Keratin associated protein 1-5   hypothetical LOC728956
<i>DUSP6</i>	-2.05	Dual specificity phosphatase 6
<b>hESF<sub>endo</sub> EP48 vs. hESF<sub>endo</sub> E48</b>		
<i>IMPA2</i>	1.66	Inositol(myo)-1(or 4)-monophosphatase 2
<i>METTL7A</i>	1.56	Methyltransferase like 7A
<i>IL1R1</i>	1.55	Interleukin 1 receptor, type I

<sup>a</sup> Comparison hESF<sub>endo</sub> EP6 versus hESF<sub>endo</sub> E6 revealed no significantly regulated genes at 1.5-fold change.



TABLE 5. List of regulated genes (BH corrected *P* value < 0.05) in comparison of hESF<sub>nonendo</sub> or hESF<sub>endo</sub> treated with E<sub>2</sub>P<sub>4</sub> for 14 days (EP14) versus hESF<sub>nonendo</sub> or hESF<sub>endo</sub> treated with E<sub>2</sub> for 14 days (E14), expressed as fold change (FC).

Gene symbol	FC	Gene description
hESF <sub>nonendo</sub> EP14 vs. hESF <sub>nonendo</sub> E14		
<i>SPARCL1</i>	27.49	SPARC-like 1 (mast9, hevln)
<i>ABI3BP</i>	23.24	ABI gene family, member 3 (NESH) binding protein
<i>P2RY14</i>	16.35	Purinergic receptor P2Y, G-protein coupled, 14
<i>IGF1</i>	6.94	Insulin-like growth factor 1 (somatomedin C)
<i>MAOB</i>	6.60	Monoamine oxidase B
<i>FKBP5 LOC285847</i>	6.37	FK506 binding protein 5   hypothetical protein LOC285847
<i>SLC7A8</i>	5.86	Solute carrier family 7 (cationic amino acid transporter, $\gamma^+$ system), member 8
<i>ENPP1</i>	5.83	Ectonucleotide pyrophosphatase/phosphodiesterase 1
<i>GPX3</i>	5.61	Glutathione peroxidase 3 (plasma)
<i>RORB</i>	5.34	RAR-related orphan receptor B
<i>IMPA2</i>	4.69	Inositol(myo)-1(or 4)-monophosphatase 2
<i>OMD</i>	3.84	Osteomodulin
<i>PRL</i>	3.78	Prolactin
<i>ADRA2C</i>	3.74	Adrenergic, alpha-2C-, receptor
<i>THSD7A</i>	3.67	Thrombospondin, type I, domain containing 7A
<i>NLGN4X</i>	3.66	Neuroigin 4, X-linked
<i>ZBTB16</i>	3.65	Zinc finger and BTB domain containing 16
<i>MYOCD</i>	3.58	Myocardin
<i>CD226</i>	3.53	CD226 molecule
<i>IGFBP1</i>	3.35	Insulin-like growth factor binding protein 1
<i>MAOA</i>	3.32	Monoamine oxidase A
<i>PLXNC1</i>	3.28	Plexin C1
<i>MOBK2B</i>	3.25	MOB1, Mps One Binder kinase activator-like 2B (yeast)
<i>MUM1L1</i>	3.20	Melanoma associated antigen (mutated) 1-like 1
<i>THBD</i>	3.19	Thrombomodulin
<i>LRIG1</i>	3.12	Leucine-rich repeats and immunoglobulin-like domains 1
<i>SORBS1</i>	2.98	Sorbin and SH3 domain containing 1
<i>INSR</i>	2.95	Insulin receptor
<i>CRISPLD2</i>	2.92	Cysteine-rich secretory protein LCCL domain containing 2
<i>CPM</i>	2.89	Carboxypeptidase M
<i>LCP1</i>	2.83	Lymphocyte cytosolic protein 1 (L-plastin)
<i>SERPINE1</i>	2.82	Serpin peptidase inhibitor, clade E (nexin, plasminogen activator inhibitor type 1), member 1
<i>C10orf10</i>	2.62	Chromosome 10 open reading frame 10
<i>CORIN</i>	2.58	Corin, serine peptidase
<i>UST</i>	2.57	Uronyl-2-sulfotransferase
<i>CNR1</i>	2.55	Cannabinoid receptor 1 (brain)
<i>ADH1B</i>	2.54	Alcohol dehydrogenase 1B (class I), beta polypeptide
<i>IL1R1</i>	2.52	Interleukin 1 receptor, type 1
<i>LASS6</i>	2.46	LAG1 homolog, ceramide synthase 6
<i>TNC</i>	2.41	Tenascin C (hexabrachion)
<i>KLF6</i>	2.36	Kruppel-like factor 6
<i>OLFML2B</i>	2.33	Olfactomedin-like 2B
<i>PRLR</i>	2.33	Prolactin receptor
<i>APCDD1</i>	2.26	Adenomatosis polyposis coli down-regulated 1
<i>ERRF1</i>	2.22	ERBB receptor feedback inhibitor 1
<i>GLB1L2</i>	2.22	Galactosidase, beta 1-like 2
<i>ACSL1</i>	2.19	Acyl-CoA synthetase long-chain family member 1
<i>RHOU</i>	2.19	Ras homolog gene family, member U
<i>PTH1H</i>	2.14	Parathyroid hormone-like hormone
<i>EFHD1</i>	2.14	EF-hand domain family, member D1
<i>SYTL4</i>	2.13	Synaptotagmin-like 4 (granophilin-a)
<i>TSC22D3</i>	2.11	TSC22 domain family, member 3
<i>TIMP3</i>	2.11	TIMP metalloproteinase inhibitor 3 (Sorsby fundus dystrophy, pseudoinflammatory)
<i>MAP3K4</i>	2.11	Mitogen-activated protein kinase kinase 4
<i>ABCC9</i>	2.08	ATP-binding cassette, sub-family C (CFTR/MRP), member 9
<i>SPSB1</i>	2.04	SplA/ryanodine receptor domain and SOCS box containing 1
<i>ENPEP</i>	2.01	Glutamyl aminopeptidase (aminopeptidase A)
<i>ADCY1</i>	2.00	Adenylate cyclase 1 (brain)
<i>C14orf147</i>	1.98	Chromosome 14 open reading frame 147
<i>APOD</i>	1.97	Apolipoprotein D
<i>IRS2</i>	1.93	Insulin receptor substrate 2
<i>ADAMTS1</i>	1.91	ADAM metalloproteinase with thrombospondin type 1 motif, 1
<i>LHFP</i>	1.91	Lipoma HMGIC fusion partner
<i>ZEB1</i>	1.88	Zinc finger E-box binding homeobox 1
<i>GPRC5B</i>	1.84	G protein-coupled receptor, family C, group 5, member B
<i>SESTD1</i>	1.83	SEC14 and spectrin domains 1
<i>PCBP3</i>	1.82	Poly(rC) binding protein 3
<i>FAM19A2</i>	1.82	Family with sequence similarity 19 (chemokine (C-C motif)-like), member A2
<i>MMD</i>	1.81	Monocyte to macrophage differentiation-associated
<i>DKK1</i>	1.80	Dickkopf homolog 1 ( <i>Xenopus laevis</i> )
<i>SLC46A3</i>	1.79	Solute carrier family 46, member 3
<i>COL4A1</i>	1.79	Collagen, type IV, alpha 1

TABLE 5. Continued.

Gene symbol	FC	Gene description
<i>METTL7A</i>	1.79	Methyltransferase like 7A
<i>ACTA2</i>	1.77	Actin, alpha 2, smooth muscle, aorta
<i>FERMT2</i>	1.76	Fermitin family homolog 2 (Drosophila)
<i>ACTG2</i>	1.76	Actin, gamma 2, smooth muscle, enteric
<i>HAND2</i>	1.76	Heart and neural crest derivatives expressed 2
<i>LMOD1</i>	1.75	Leiomodin 1 (smooth muscle)
<i>TMEM37</i>	1.74	Transmembrane protein 37
<i>NBLA00301</i>	1.71	Nbla00301
<i>IRF6</i>	1.70	Interferon regulatory factor 6
<i>CFH</i>	1.70	Complement factor H
<i>SULF2</i>	1.67	Sulfatase 2
<i>CD302</i>	1.66	CD302 molecule
<i>ULK4</i>	1.66	Unc-51-like kinase 4 (C. elegans)
<i>GCNT1</i>	1.65	Glucosaminyl (N-acetyl) transferase 1, core 2 (beta-1,6-N-Acetylglucosaminyltransferase)
<i>ABHD5</i>	1.65	Abhydrolase domain containing 5
<i>MITF</i>	1.64	Microphthalmia-associated transcription factor
<i>PPAP2B</i>	1.64	Phosphatidic acid phosphatase type 2B
<i>CFHR1</i>	1.64	Complement factor H-related 1
<i>ITGA10</i>	1.61	Integrin, alpha 10
<i>AKAP13</i>	1.61	A kinase (PRKA) anchor protein 13
<i>ADH1C</i>	1.60	Alcohol dehydrogenase 1C (class I), gamma polypeptide
<i>ADAMTS2</i>	1.59	ADAM metalloproteinase with thrombospondin type 1 motif, 2
<i>SLC41A2</i>	1.59	Solute carrier family 41, member 2
<i>ID3</i>	1.59	Inhibitor of DNA binding 3, dominant negative helix-loop-helix protein
<i>PRR15</i>	1.58	Proline rich 15
<i>HSD17B11</i>	1.58	Hydroxysteroid (17-beta) dehydrogenase 11
<i>SORT1</i>	1.58	Sortilin 1
<i>JAK2</i>	1.58	Janus kinase 2 (a protein tyrosine kinase)
<i>AVPR1A</i>	1.57	Arginine vasopressin receptor 1A
<i>CHSY3</i>	1.57	Chondroitin sulfate synthase 3
<i>ZCCHC6</i>	1.57	Zinc finger, CCHC domain containing 6
<i>NFIL3</i>	1.57	Nuclear factor, interleukin 3 regulated
<i>EMP2</i>	1.56	Epithelial membrane protein 2
<i>PEMT</i>	1.56	Phosphatidylethanolamine N-methyltransferase
<i>RASL11A</i>	1.55	RAS-like, family 11, member A
<i>ANTXR2</i>	1.55	Anthrax toxin receptor 2
<i>KIAA1217</i>	1.55	KIAA1217
<i>DIAPH2</i>	1.55	Diaphanous homolog 2 (Drosophila)
<i>CHST7</i>	1.55	Carbohydrate (N-acetylglucosamine 6-O) sulfotransferase 7
<i>KCNK6</i>	1.54	Potassium channel, subfamily K, member 6
<i>MTR</i>	1.52	5-Methyltetrahydrofolate-homocysteine methyltransferase
<i>CCDC102B</i>	1.52	Coiled-coil domain containing 102B
<i>KLHL23 PHOSPHO2</i>	1.51	Kelch-like 23 (Drosophila)   phosphatase, orphan 2
<i>ABLIM1</i>	1.51	Actin binding LIM protein 1
<i>ID4</i>	1.51	Inhibitor of DNA binding 4, dominant negative helix-loop-helix protein
<i>PHF17</i>	1.51	PHD finger protein 17
<i>FOXO1</i>	1.50	Forkhead box O1
<i>TMED8</i>	1.50	Transmembrane emp24 protein transport domain containing 8
<i>TLR4</i>	1.50	Toll-like receptor 4
<i>GREB1</i>	1.50	Growth regulation by estrogen in breast cancer 1
<i>C2orf59 LOC541471</i>	-1.50	Chromosome 2 open reading frame 59   hypothetical LOC541471
<i>GREM1</i>	-1.51	Gremlin 1, cysteine knot superfamily, homolog (Xenopus laevis)
<i>SYT16</i>	-1.52	Synaptotagmin XVI
<i>FLJ36031</i>	-1.52	Hypothetical protein FLJ36031
<i>IFIT1</i>	-1.53	Interferon-induced protein with tetratricopeptide repeats 1
<i>ARHGAP18</i>	-1.54	Rho GTPase activating protein 18
<i>ETV5</i>	-1.54	Ets variant gene 5 (ets-related molecule)
<i>SNRK</i>	-1.54	SNF related kinase
<i>LOXL4</i>	-1.55	Lysyl oxidase-like 4
<i>LIMA1</i>	-1.55	LIM domain and actin binding 1
<i>CYFIP2</i>	-1.56	Cytoplasmic FMR1 interacting protein 2
<i>INPP4B</i>	-1.57	Inositol polyphosphate-4-phosphatase, type II, 105kDa
<i>C6orf138</i>	-1.58	Chromosome 6 open reading frame 138
<i>IL13RA2</i>	-1.58	Interleukin 13 receptor, alpha 2
<i>CCND1</i>	-1.60	Cyclin D1
<i>NAV3</i>	-1.61	Neuron navigator 3
<i>ISOC1</i>	-1.61	Isochorismatase domain containing 1
<i>SAMD12</i>	-1.62	Sterile alpha motif domain containing 12
<i>HSPC159</i>	-1.64	Galectin-related protein
<i>BDKRB1</i>	-1.64	Bradykinin receptor B1
<i>NT5E</i>	-1.65	5'-Nucleotidase, ecto (CD73)
<i>MYO1B</i>	-1.67	Myosin IB
<i>SERPINB2</i>	-1.67	Serpin peptidase inhibitor, clade B (ovalbumin), member 2

TABLE 5. Continued.

Gene symbol	FC	Gene description
<i>SDC4</i>	-1.68	Syndecan 4
<i>SMAD3</i>	-1.69	SMAD family member 3
<i>HERC5</i>	-1.69	Hect domain and RLD 5
<i>PLCB1</i>	-1.69	Phospholipase C, beta 1 (phosphoinositide-specific)
<i>IGFBP6</i>	-1.70	Insulin-like growth factor binding protein 6
<i>AFAP1L2</i>	-1.75	Actin filament associated protein 1-like 2
<i>FAM43A</i>	-1.76	Family with sequence similarity 43, member A
<i>RAB3B</i>	-1.83	RAB3B, member RAS oncogene family
<i>KRTAP1-4 LOC728952 LOC730743</i>	-1.83	Similar to keratin associated protein 1-1   hypothetical LOC728952
<i>ST8SIA1</i>	-1.86	ST8 alpha-N-acetyl-neuraminide alpha-2,8-sialyltransferase 1
<i>RGS4</i>	-1.87	Regulator of G-protein signaling 4
<i>PTN</i>	-1.89	Pleiotrophin (heparin binding growth factor 8, neurite growth-promoting factor 1)
<i>ARL4C</i>	-1.90	ADP-ribosylation factor-like 4C
<i>FJX1</i>	-1.97	Four jointed box 1 (Drosophila)
<i>NEFM</i>	-1.97	Neurofilament, medium polypeptide 150kDa
<i>FHOD3</i>	-2.03	Formin homology 2 domain containing 3
<i>ATP8B1</i>	-2.05	ATPase, class I, type 8B, member 1
<i>F2RL2</i>	-2.12	Coagulation factor II (thrombin) receptor-like 2
<i>IGFBP5</i>	-2.15	Insulin-like growth factor binding protein 5
<i>KRT34</i>	-2.17	Keratin 34
<i>DUSP6</i>	-2.18	Dual specificity phosphatase 6
<i>C4orf31</i>	-2.20	Chromosome 4 open reading frame 31
<i>PROM1</i>	-2.23	Prominin 1
<i>STC1</i>	-2.29	Stanniocalcin 1
<i>CCRL1</i>	-2.52	Chemokine (C-C motif) receptor-like 1
<i>GBP4</i>	-2.54	Guanylate binding protein 4
<i>KRTAP1-5 LOC728956</i>	-2.67	Keratin associated protein 1-5   hypothetical LOC728956
hESF <sub>endo</sub> EP14 vs. hESF <sub>endo</sub> E14		
<i>C10orf10</i>	1.66	Chromosome 10 open reading frame 10
<i>SLC7A8</i>	1.61	Solute carrier family 7 (cationic amino acid transporter, y+ system), member 8
<i>ADH1B</i>	1.60	Alcohol dehydrogenase 1B (class I), beta polypeptide
<i>IL1R1</i>	1.59	Interleukin 1 receptor, type I

Tables 3–5 and Supplemental Tables S1–S3). Significantly regulated canonical pathways and network formations in response to E<sub>2</sub>P<sub>4</sub> versus that of E<sub>2</sub> treatment in hESF<sub>nonendo</sub> and hESF<sub>endo</sub> and in hESF<sub>endo</sub> versus hESF<sub>nonendo</sub> are shown in Supplemental Tables S4 and S5.

**Canonical pathways.** Canonical pathways regulated at early and intermediate time points in the hESF<sub>nonendo</sub> response to E<sub>2</sub>P<sub>4</sub> versus E<sub>2</sub> treatment were related to lipid and carbohydrate metabolism, O-glycan biosynthesis, neuregulin, and cAMP signaling. At 14 days, there was activation of the IGF1 signaling and integrin-linked kinase (ILK) pathways and activation by the VDR/RXR and hepatic fibrosis pathways. In contrast, the hESF<sub>endo</sub> response to E<sub>2</sub>P<sub>4</sub> versus E<sub>2</sub> treatment was blunted, with fewer genes being regulated and subsequently being involved in canonical pathways. Moreover, pathways activated in hESF<sub>endo</sub> differed from those activated in hESF<sub>nonendo</sub> in response to E<sub>2</sub>P<sub>4</sub> versus E<sub>2</sub> treatment. Differences were observed in interleukin (IL)<sub>10</sub> and IL6 signaling pathways, PPAR signaling, LXR/RXR activation, and bile acid and glucose biosynthesis and metabolism pathways in early and late responses to E<sub>2</sub>P<sub>4</sub> versus E<sub>2</sub> treatment (Supplemental Table S4).

**Networks.** Network analysis of genes upregulated in the early (6-h) response to E<sub>2</sub>P<sub>4</sub> versus E<sub>2</sub> treatment in hESF<sub>nonendo</sub> revealed enrichment of biological processes involving carbohydrate, lipid, and amino acid metabolism and tissue morphology. In contrast, in the (48-h) intermediate response, disease and development-associated networks prevailed, including cancer, cardiovascular, and gastrointestinal disease, tissue development, cell morphology, and embryonic development. The late response of hESF<sub>nonendo</sub> at 14 days showed involvement of networks including DNA replication, recombination, and repair, nucleic acid metabolism, skeletal and

muscular system development and function, endocrine system disorders, and gene expression. IPA analysis of the hESF<sub>endo</sub> early response involved tissue developmental processes (nervous system, skeletal, muscular, connective tissue, and hematologic) and cell–cell signaling and cell cycle. The intermediate response revealed the formation of cancer, cell death, neurological disease, posttranslational modification, cell cycle, cellular development, and cell signaling networks, which differs from the hESF<sub>nonendo</sub> response at this time point. Differences between hESF<sub>endo</sub> and hESF<sub>nonendo</sub> at 14 days of treatment revealed networks involving cancer, cell growth and proliferation, cell–cell signaling, cell movement, nucleic acids, drugs, and lipid metabolism (Supplemental Table S5).

## DISCUSSION

### General Comments

This study reveals for the first time the kinetic expressions of specific genes, pathways, and networks during early, intermediate, and late responses to P<sub>4</sub> (E<sub>2</sub>P<sub>4</sub> vs. E<sub>2</sub>) in hESF from women with and without endometriosis. In this in vitro model, there are likely a multiplicity of pathways and processes that are initiated and perhaps synergistically affected by E<sub>2</sub>P<sub>4</sub> treatment and separately by E<sub>2</sub> treatment, although the response to E<sub>2</sub> was significantly limited to PGR upregulation at all time points, supporting the data obtained herein as likely to be P<sub>4</sub>-mediated events. Nonetheless, there may be other responses that are not strictly P<sub>4</sub>-mediated in our model; however, identifying the classically P<sub>4</sub>-regulated genes was consistent with the effectiveness of a functional P<sub>4</sub> pathway in hESF<sub>nonendo</sub> and a dysfunctional pathway in hESF<sub>endo</sub>.

In hESF<sub>nonendo</sub>, distinct biological and molecular processes and signaling pathways were observed; whereas, signaling

pathways in the hESF<sub>endo</sub> responses to E<sub>2</sub>P<sub>4</sub> versus E<sub>2</sub> treatment were not active compared to those in hESF<sub>nonendo</sub>, due to the limited number of genes regulated. A blunted hESF<sub>endo</sub> response to P<sub>4</sub> was observed, with limited expression of many P<sub>4</sub>-regulated genes and curtailed activation of distinct canonical pathways and processes. While the *PGRB/PGRA* ratio was reported to be lower in endometrial tissues from women with endometriosis than in tissues from healthy volunteers [15], our earlier studies of eutopic endometrium did not confirm significant differences in *PGR* isoforms in either tissue biopsies or hESF from women with endometriosis versus those without endometriosis [10]. In the present study, we hypothesized and have found that the P<sub>4</sub> resistance in eutopic endometrium from women with endometriosis results not from the *PGR* aberrant expression but rather from its delayed upregulation in the early response to E<sub>2</sub>. Moreover, in the current study, the *PGR* FKBP5 (immunophilin) chaperone expression level, which was upregulated in hESF<sub>nonendo</sub> in early, intermediate, and late responses to P<sub>4</sub>, was not regulated in hESF<sub>endo</sub> and was significantly lower in hESF<sub>endo</sub> than in hESF<sub>nonendo</sub> at *t* = 0. Interestingly, diminished FKBP4 expression has been observed in eutopic and ectopic endometrium in humans and baboons with endometriosis [27, 28]. Furthermore, *Fkbp4*-null mice are prone to develop endometriotic lesions upon inoculation with endometrial tissue [28]. Overall, *PGR* chaperones (and coregulators [10]) appear to play a role in the blunted response of hESF to P<sub>4</sub> in women with endometriosis.

We propose that the normal response of hESF to P<sub>4</sub> (E<sub>2</sub>P<sub>4</sub> vs. E<sub>2</sub>) involves a tightly regulated kinetic cascade involving key components in the *PGR* and *MAPK* signaling pathways that results in inhibition of E<sub>2</sub>-mediated proliferation, establishment of key networks, and eventual differentiation to the decidual phenotype. Furthermore, we propose that these early events, which are likely temporal and spatial in nature, are not established in the early hESF<sub>endo</sub> response to P<sub>4</sub>, contributing to abnormal P<sub>4</sub> responsiveness of this cell type in eutopic endometrium of women with endometriosis. A similar mechanism may be ongoing in ectopic foci.

Our earlier studies using eutopic endometrial tissue samples from women with and without endometriosis [25, 26] revealed dysregulation of a number of P<sub>4</sub>-responsive genes and signaling molecules. In those earlier studies we specifically validated the dysregulation of the primarily stromal fibroblast (hESF) products *ERRF1*, *FOXO1A*, *CDC2*, *IGFBP1*, *PRL*, *GPX3*, and *DKK1* in endometrial tissue from women with disease [25, 26]. Many of these gene products were found to be similarly dysregulated in our current in vitro study of hESF, and thus, essentially their in vivo expression has been validated by our previous work.

#### *hESF<sub>nonendo</sub> Response to Progesterone*

**Early and intermediate responses.** The first observable response to P<sub>4</sub> in vivo occurs in early secretory endometrium and includes P<sub>4</sub> inhibition of E<sub>2</sub>-induced cellular proliferation and an increase in cholesterol, fatty acid, prostaglandin, glycogen, and transporter biosynthesis, mostly in epithelium, with little known about the early hESF response [8]. In mid-secretory endometrium, hESF begin to make a transition from a fibroblast-like spindle to a rounder morphology and a secretory phenotype, typical of epithelium, producing classical “decidual markers” (e.g., prolactin and *IGFBP1*). In vitro, hESF respond to P<sub>4</sub> (plus E<sub>2</sub>), P<sub>4</sub> plus cAMP, or only cAMP, with characteristic morphologic and gene expression and protein changes, as in vivo. Treating cells with cAMP or P<sub>4</sub> plus cAMP

results in upregulation of decidual markers within 48–72 h, compared to 8–14 days (as in vivo [12]), with P<sub>4</sub> treatment alone. Direct transcriptional control by P<sub>4</sub> has been questioned due to the time course in vivo [12], and P<sub>4</sub> has been proposed to maintain the decidual response initiated by a yet-to-be identified ligand stimulating the *PKA* pathway [12]. The data herein support an early response to P<sub>4</sub> that includes unique early response genes and intracellular signaling pathways and subsequent expression of decidual markers involving stimulation of the *PKA* pathway.

What is striking in the early hESF<sub>nonendo</sub> response to P<sub>4</sub> is *EGFR*-mediated and *MAPK* signaling. The *ERBB* receptor feedback inhibitor 1 (*ERRF1*, or mitogen-inducible gene 6 [*MIG6*]) is a negative regulator of *EGFR*-mediated mitogenic signaling [29] and is one of the earliest transcription factors upregulated in P<sub>4</sub>-treated hESF. The protein regulates the duration of *MAPK* activation via attenuation of *EGFR* autophosphorylation in a mouse knockout model [29]. Our data support P<sub>4</sub> regulation of this signaling pathway early in the P<sub>4</sub> response in hESF<sub>nonendo</sub>.

Other early and intermediate response genes upregulated in the hESF<sub>nonendo</sub> response to P<sub>4</sub> (E<sub>2</sub>P<sub>4</sub> vs. E<sub>2</sub>) are the *DKK1* gene of the *Wnt* family, the solute carrier family *SLC7A8* and *IMPA2* proteins, and, interestingly, the adrenergic receptor alpha-2C (*ADRA2C*) gene; this last gene is one of several neuronal receptors found in endometrium [24, 30]. Expression of the *ADRA2C* transcript in P<sub>4</sub>-treated hESF<sub>nonendo</sub> suggests that normal endometrium possesses the machinery for regulating neurotransmission [31]. Marked *IMPA2* upregulation underscores the importance of the phosphatidylinositol signaling pathway [32] in the response of hESF to P<sub>4</sub>.

The *SPARCL1* protein (a *SPARC*-like 1 [hevin], or mast9, or high endothelial venule protein), an extracellular matrix-associated protein member of the *SPARC* family, is upregulated during the implantation window and is associated with the E<sub>2</sub>P<sub>4</sub> versus the E<sub>2</sub> response of cultured explants from late proliferative phase human endometrium [33]. It is expressed in many tissues and is associated with collagen fibrils [34]. *SPARCL1* expression is downregulated in several tumors and negatively regulates cell cycle progression, cell proliferation, and migration [35, 36]. In the present study, *SPARCL1* expression was highly upregulated in response to P<sub>4</sub> in hESF<sub>nonendo</sub> at 6 and 48 h and 14 days, suggesting a major role for the protein product in the P<sub>4</sub> response of hESF, perhaps participating in or directly inhibiting cell cycle progression and enabling differentiation in response to P<sub>4</sub>.

**Late response.** At 14 days, genes corresponding to secretory and cell adhesion proteins, including classical decidual markers, as well as interleukins, signaling components, enzymes, and receptors, are upregulated (Table 5), with the *SPARCL1* gene mentioned above being the most highly upregulated gene. Also of interest is the *CNRI* cannabinoid receptor, shown recently to be expressed in human endometrium throughout the cycle, without significant cyclic variations [37]. Although P<sub>4</sub> has been shown to activate the endocannabinoid-degrading enzyme fatty acid amide hydrolase in human lymphocytes [38], this is the first study of P<sub>4</sub> regulation of the endocannabinoid system in human endometrium. The significance of *CNRI* expression in hESF warrants further investigation.

One of the most highly upregulated genes, *ENPP1*, regulates extracellular pyrophosphate, a major inhibitor of extracellular matrix (ECM) calcification [39]. Also, by Day 14, many known P<sub>4</sub>-regulated genes are increased, and several genes associated with actin filaments and bundle formation are up- or downregulated (Table 5), consistent with changes in cell

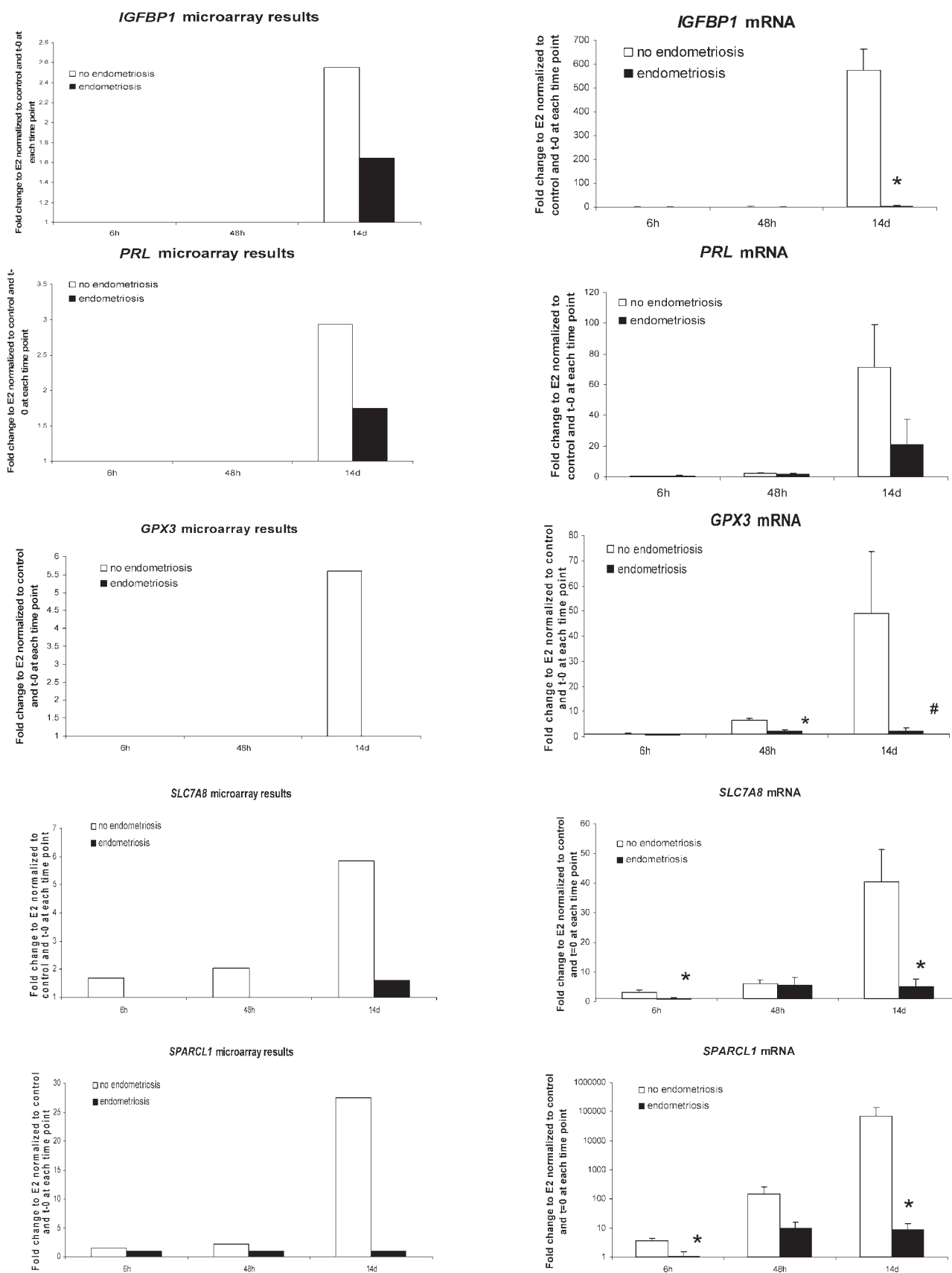


FIG. 3. Validation of microarray gene expression profiling by QRT-PCR. **Right column** indicates fold change expression of genes in the microarray data set in the present study. **Left column** indicates QRT-PCR validation of microarray data of gene expression in  $hESF_{nonendo}$  and  $hESF_{endo}$  treated with or without  $E_2$  and  $P_4$  for 6 h, 48 h, and 14 days ( $n=4$  in each group). Y axis displays the fold change of expression in  $hESF$  treated with  $P_4$  and  $E_2$ , relative to  $E_2$  and normalized to the vehicle control and  $t=0$  at each time point. \*, Significance accepted at  $P \leq 0.05$ . #, Significance accepted at  $P = 0.05$ . Error bars represent means  $\pm$  SEM.

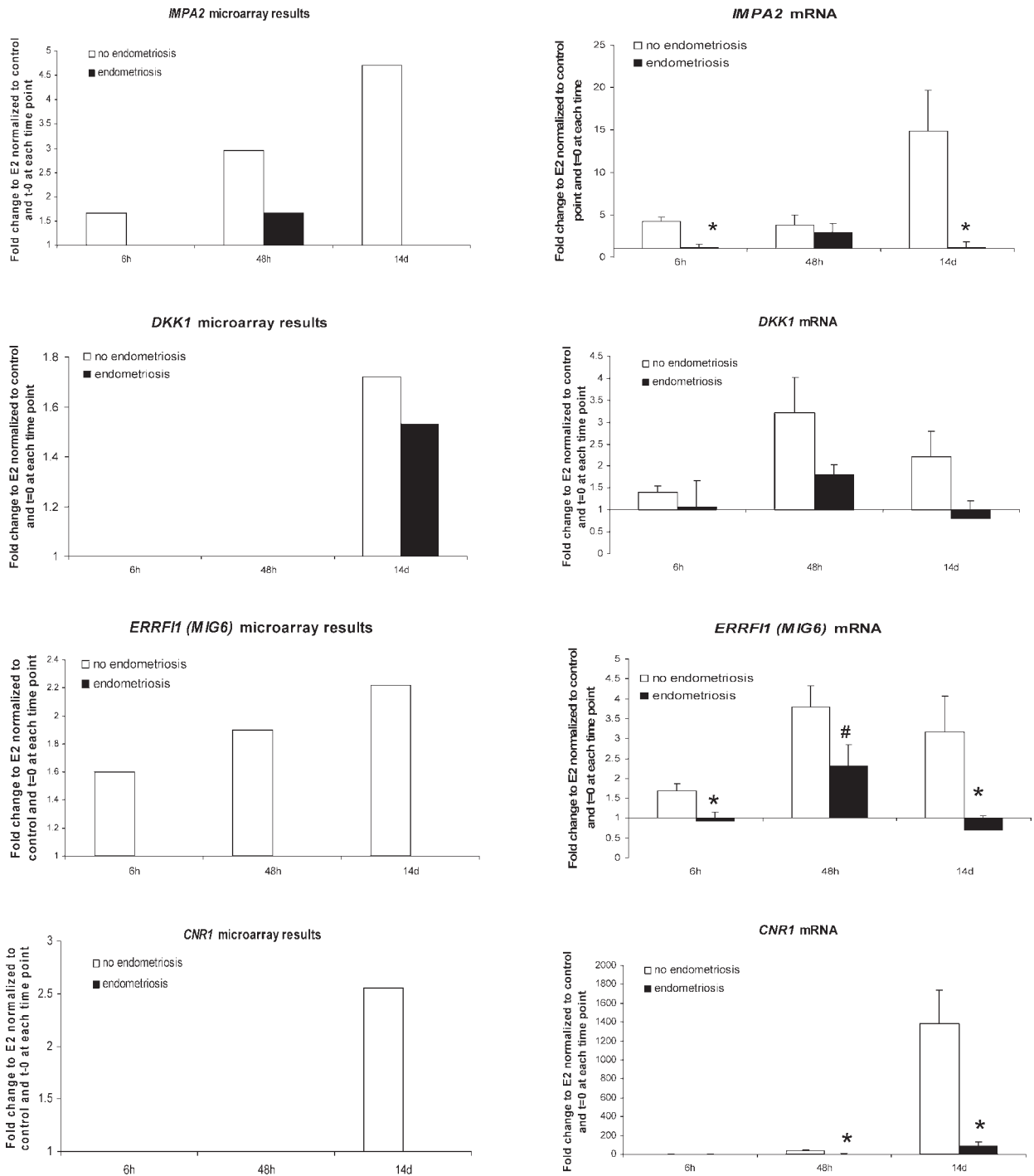


FIG. 3. Continued.

shape in the late response to  $P_4$ . Thus, the gene expression profile at Day 14 represents classically decidualizing hESF, based on the cytoskeletal and stress fiber changes, the secretory phenotype, and a predominance of genes involved in the ECM, cell matrix, and cell-cell communication.

Several groups have investigated the transcriptome of decidualized human hESF (summarized in Supplemental Table S6). The current study compared hESF treated with  $E_2P_4$  versus  $E_2$  and showed a time course of this comparison, focusing on early, intermediate, and late responses to  $P_4$ , per se, of hESF (both hESF<sub>nonendo</sub> and hESF<sub>endo</sub>). Okada and

colleagues [40] analyzed genes expressed in hESF<sub>nonendo</sub> after 3 days of  $P_4$  treatment (without  $E_2$ ) using a 1000-gene cDNA platform and found 6 genes were upregulated and 27 genes were downregulated by  $P_4$ , compared to controls (vehicle alone). Among those downregulated was the *IGFBP5* gene and pregnancy-specific glycoproteins, and among those upregulated was the *IL1RI* gene, as also found herein. The differences observed between the two studies were probably due to different treatment protocols (e.g., no priming with  $E_2$ ), duration of hormonal treatments, and use of different array platforms.

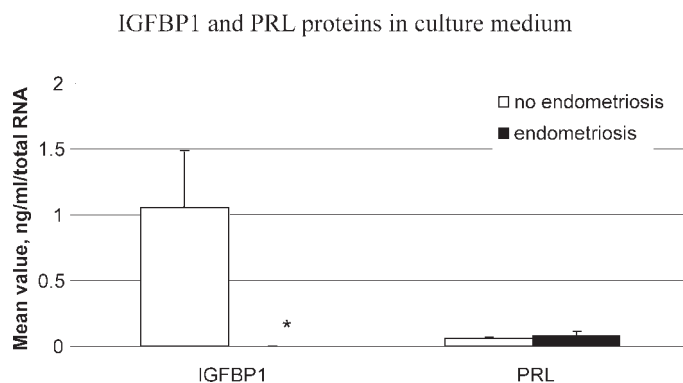


FIG. 4. Validation of microarray gene expression profiling by ELISA. IGFBP1 and PRL protein secretion in CM from hESF<sub>nonendo</sub> and hESF<sub>endo</sub> treated with or without E<sub>2</sub> and P<sub>4</sub> for 14 days (n = 4 in each group), normalized to the total RNA level. \*, Significance accepted at  $P \leq 0.05$ . Error bars represent means  $\pm$  SEM.

### hESF<sub>endo</sub> Response to Progesterone

*Early, intermediate, and late responses.* There were significantly lower numbers of genes regulated by P<sub>4</sub> (E<sub>2</sub>P<sub>4</sub> vs. E<sub>2</sub>) in hESF<sub>endo</sub> versus hESF<sub>nonendo</sub> (Tables 4, 5). In women with endometriosis, in contrast to those without disease, ERRFI1 is not upregulated in secretory phase tissue [25, 41], further supporting its regulation by P<sub>4</sub> and dysregulation in this P<sub>4</sub>-resistant disorder, confirmed herein on the cellular level. We have previously shown that increased activation of MAPK1/3 in hESF<sub>endo</sub> contributes to persistent proliferative changes in secretory-phase endometrium in women with endometriosis [41]. Constitutive expression of the AREG and HBEGF EGFR ligands in hESF<sub>endo</sub> that can activate MAPK1/3 [42–44], and were observed herein, provides a potential mechanism for the observed constitutive MAPK1/3 phosphorylation and the proliferative phenotype of hESF<sub>endo</sub>. This may play an important role in the pathophysiology of the disease and design of targeted therapies for endometriosis and is under study in our laboratory.

We previously analyzed transcriptomes of hESF (both hESF<sub>nonendo</sub> and hESF<sub>endo</sub>) in response to 8-Br-cAMP for 96 h (full decidualization phenotype) [9]. A comparison of lists of genes of decidualized hESF<sub>nonendo</sub> in response to P<sub>4</sub> (14 days) versus those of 8-Br-cAMP (96 h) revealed 30 common genes, among them *PRL*, *IGFBP1*, *ADRA2C*, *CCND1*, *ILIR1*, and stanniocalcin (Supplemental Table S7), reflecting the decidualization signature of hESF<sub>nonendo</sub>. Of note, no common genes were found when similar comparisons were performed with hESF<sub>endo</sub> (Supplemental Table S7).

Herein, the (*CCND1*) cyclin D1 transcript was increased in hESF<sub>endo</sub> versus hESF<sub>nonendo</sub> treated with E<sub>2</sub>P<sub>4</sub> for 14 days, while it was decreased in hESF<sub>nonendo</sub> in response to P<sub>4</sub> (E<sub>2</sub>P<sub>4</sub> vs. E<sub>2</sub>). This confirms our previous results showing an increased proliferative potential with increased *CCND1* expression in decidualized hESF<sub>endo</sub> versus hESF<sub>nonendo</sub> and a blunted response of hESF<sub>endo</sub> to cAMP (decreased PKA activation in hESF<sub>endo</sub> here) [9, 41].

In contrast to the upregulation of the *SPARCL1* gene in response to P<sub>4</sub> in hESF<sub>nonendo</sub>, *SPARCL1* expression was not regulated by P<sub>4</sub> in hESF<sub>endo</sub>. Importantly, it was the most downregulated gene in hESF<sub>endo</sub> versus hESF<sub>nonendo</sub>, underscoring the decreased responsiveness of hESF<sub>endo</sub> to P<sub>4</sub> treatment. As *SPARCL1* expression is an inhibitor of cell proliferation, its upregulation in decidualized hESF<sub>nonendo</sub> and

downregulation in hESF<sub>endo</sub> suggest a role for it in the proliferative phenotype of hESF<sub>endo</sub>.

Interestingly, cancer-associated signaling pathways, such as those in colorectal cancer metastasis and bladder cancer signaling, were regulated in hESF<sub>endo</sub> versus hESF<sub>nonendo</sub> (Supplemental Table S4). Regulation of these canonical pathways in hESF<sub>endo</sub> is consistent with the invasive phenotype of endometriosis that may be shared by other invasive cell types and tissues.

Among several signaling pathways that were significantly dysregulated in the hESF<sub>endo</sub> response to P<sub>4</sub>, versus that of hESF<sub>nonendo</sub> (Supplemental Table S4), are those involving axonal guidance and neuropathic pain signaling ( $P = 0.0048$  and  $P = 0.01$ , respectively) (Supplemental Table S4). Adrenergic and sensory nerve fibers have recently been described in eutopic endometrium of women with endometriosis (but not in women without endometriosis) [45], which may contribute to pain associated with the disorder. Thus, it is of particular interest that in the hESF<sub>nonendo</sub> response to P<sub>4</sub> (E<sub>2</sub>P<sub>4</sub> vs. E<sub>2</sub>), there is sustained *ADRA2C* upregulation and downregulation of neurofilament medium polypeptide (*NEFM*) and pleiotrophin (heparin-binding growth factor 8, neurite growth-promoting factor 1). Pleiotrophin, associated with angiogenesis and neurite growth, is expressed in normal endometrium throughout the menstrual cycle and is significantly upregulated in endometrium from women with advanced-stage endometriosis [46]. The molecular mechanisms underlying the presence of nerve fibers within eutopic endometrium of women with endometriosis are not well understood; however, the data herein support a role for hESF in promoting neurite growth and axonal guidance within the endometrium of women with endometriosis and, potentially, hormonal regulation of nerve fibers and nerve bundle density in this tissue from women with disease [47]. We are currently investigating this in our laboratory.

The current study has given unique insight into the genome-wide transcriptome of the human endometrial stromal fibroblast at early, intermediate, and late responses to P<sub>4</sub>, in an experimental paradigm that reveals kinetic changes in gene expression, biological processes, and signaling pathways. Some of these changes are novel and some are consistent with known hESF responses to P<sub>4</sub> in vivo and resistance to P<sub>4</sub> actions and dysregulation in disorders such as endometriosis. The signaling pathways described herein may serve as unique targets for drugs to treat endometrial disorders.

### REFERENCES

- Cramer DW, Missmer SA. The epidemiology of endometriosis. *Ann N Y Acad Sci* 2002; 955:11–22.
- Eskenazi B, Warner ML. Epidemiology of endometriosis. *Obstet Gynecol Clin NorthAm* 1997; 24:235–258.
- Giudice LC. Clinical practice. Endometriosis. *N Engl J Med* 2010; 362: 2389–2398.
- Aghajanova L, Velarde MC, Giudice LC. Altered gene expression profiling in endometrium: evidence for progesterone resistance. *Semin Reprod Med* 2010; 28:51–58.
- Bulun SE. Endometriosis. *N Engl J Med* 2009; 360:268–279.
- Giudice LC. Endometrium in PCOS: Implantation and predisposition to endocrine CA. *Best Pract Res Clin Endocrinol Metab* 2006; 20:235–244.
- Irwin JC, Giudice LC. The decidua. In: Knobil E, Neill JD (eds.), *Encyclopedia of Reproduction*. San Diego: Academic Press; 1998:823–835.
- Giudice LC. Application of functional genomics to primate endometrium: insights into biological processes. *Reprod Biol Endocrinol* 2006; 4(suppl 1):S4.
- Aghajanova L, Horcajadas JA, Weeks JL, Esteban FJ, Nezhat CN, Conti M, Giudice LC. The protein kinase A pathway-regulated transcriptome of endometrial stromal fibroblasts reveals compromised differentiation and persistent proliferative potential in endometriosis. *Endocrinology* 2010; 151:1341–1355.
- Aghajanova L, Velarde MC, Giudice LC. The progesterone receptor

- coactivator Hic-5 is involved in the pathophysiology of endometriosis. *Endocrinology* 2009; 150:3863–3870.
11. Brar AK, Frank GR, Kessler CA, Cedars MI, Handwerger S. Progesterone-dependent decidualization of the human endometrium is mediated by cAMP. *Endocrine* 1997; 6:301–307.
  12. Gellersen B, Brosens J. Cyclic AMP and progesterone receptor cross-talk in human endometrium: a decidualizing affair. *J Endocrinol* 2003; 178: 357–372.
  13. Jones MC, Fusi L, Higham JH, Abdel-Hafiz H, Horwitz KB, Lam EW, Brosens JJ. Regulation of the SUMO pathway sensitizes differentiating human endometrial stromal cells to progesterone. *Proc Natl Acad Sci U S A* 2006; 103:16272–16277.
  14. Attia GR, Zeitoun K, Edwards D, Johns A, Carr BR, Bulun SE. Progesterone receptor isoform A but not B is expressed in endometriosis. *J Clin Endocrinol Metab* 2000; 85:2897–2902.
  15. Igarashi TM, Bruner-Tran KL, Yeaman GR, Lessey BA, Edwards DP, Eisenberg E, Osteen KG. Reduced expression of progesterone receptor-B in the endometrium of women with endometriosis and in cocultures of endometrial cells exposed to 2,3,7,8-tetrachlorodibenzo-p-dioxin. *Fertil Steril* 2005; 84:67–74.
  16. Xue Q, Lin Z, Cheng YH, Huang CC, Marsh E, Yin P, Milad MP, Confino E, Reierstad S, Innes J, Bulun SE. Promoter methylation regulates estrogen receptor 2 in human endometrium and endometriosis. *Biol Reprod* 2007; 77:681–687.
  17. Xue Q, Lin Z, Yin P, Milad MP, Cheng YH, Confino E, Reierstad S, Bulun SE. Transcriptional activation of steroidogenic factor-1 by hypomethylation of the 5' CpG island in endometriosis. *J Clin Endocrinol Metab* 2007; 92:3261–3267.
  18. Bulun SE, Utsunomiya H, Lin Z, Yin P, Cheng YH, Pavone ME, Tokunaga H, Trukhacheva E, Attar E, Gurates B, Milad MP, Confino E, et al. Steroidogenic factor-1 and endometriosis. *Mol Cell Endocrinol* 2009; 300:104–108.
  19. Klemmt PA, Carver JG, Kennedy SH, Koninckx PR, Mardon HJ. Stromal cells from endometriotic lesions and endometrium from women with endometriosis have reduced decidualization capacity. *Fertil Steril* 2006; 85:564–572.
  20. Kim JJ, Taylor HS, Lu Z, Ladhani O, Hastings JM, Jackson KS, Wu Y, Guo SW, Fazleabas AT. Altered expression of HOXA10 in endometriosis: potential role in decidualization. *Mol Hum Reprod* 2007; 13:323–332.
  21. Revised American Fertility Society classification of endometriosis. *Fertil Steril* 1985; 43:351–352.
  22. Aghajanova L, Hamilton A, Kwintkiewicz J, Vo KC, Giudice LC. Steroidogenic enzyme and key decidualization marker dysregulation in endometrial stromal cells from women with versus without endometriosis. *Biol Reprod* 2009; 80:105–114.
  23. Tulac S, Overgaard MT, Hamilton AE, Jumbe NL, Suchanek E, Giudice LC. Dickkopf-1, an inhibitor of Wnt signaling, is regulated by progesterone in human endometrial stromal cells. *J Clin Endocrinol Metab* 2006; 91:1453–1461.
  24. Talbi S, Hamilton AE, Vo KC, Tulac S, Overgaard MT, Dosiou C, Le Shay N, Nezhat CN, Kempson R, Lessey BA, Nayak NR, Giudice LC. Molecular phenotyping of human endometrium distinguishes menstrual cycle phases and underlying biological processes in normo-ovulatory women. *Endocrinology* 2006; 147:1097–1121.
  25. Burney RO, Talbi S, Hamilton AE, Vo KC, Nyegaard M, Nezhat CR, Lessey BA, Giudice LC. Gene expression analysis of endometrium reveals progesterone resistance and candidate susceptibility genes in women with endometriosis. *Endocrinology* 2007; 148:3814–3826.
  26. Kao LC, Germeyer A, Tulac S, Lobo S, Yang JP, Taylor RN, Osteen K, Lessey BA, Giudice LC. Expression profiling of endometrium from women with endometriosis reveals candidate genes for disease-based implantation failure and infertility. *Endocrinology* 2003; 144:2870–2881.
  27. Jackson KS, Brudney A, Hastings JM, Mavrogianis PA, Kim JJ, Fazleabas AT. The altered distribution of the steroid hormone receptors and the chaperone immunophilin FKBP52 in a baboon model of endometriosis is associated with progesterone resistance during the window of uterine receptivity. *Reprod Sci* 2007; 14:137–150.
  28. Hirota Y, Tranguch S, Daikoku T, Hasegawa A, Osuga Y, Taketani Y, Dey SK. Deficiency of immunophilin FKBP52 promotes endometriosis. *Am J Pathol* 2008; 173:1747–1757.
  29. Ferby I, Reschke M, Kudlacek O, Knyazev P, Pante G, Amann K, Sommergruber W, Kraut N, Ullrich A, Fassler R, Klein R. Mig6 is a negative regulator of EGF receptor-mediated skin morphogenesis and tumor formation. *Nat Med* 2006; 12:568–573.
  30. Popovici RM, Kao LC, Giudice LC. Discovery of new inducible genes in vitro decidualized human endometrial stromal cells using microarray technology. *Endocrinology* 2000; 141:3510–3513.
  31. Kohli U, Muszkat M, Sofowora GG, Harris PA, Friedman EA, Dupont WD, Scheinin M, Wood AJ, Stein CM, Kurnik D. Effects of variation in the human alpha2A- and alpha2C-adrenoceptor genes on cognitive tasks and pain perception. *Eur J Pain* 2010; 14:154–159.
  32. Yoshikawa T, Turner G, Esterling LE, Sanders AR, Detera-Wadleigh SD. A novel human myo-inositol monophosphatase gene, IMP.18p, maps to a susceptibility region for bipolar disorder. *Mol Psychiatry* 1997; 2:393–397.
  33. Dassen H, Punyadeera C, Kamps R, Klomp J, Dunselman G, Dijcks F, de Goeij A, Ederveen A, Groothuis P. Progesterone regulation of implantation-related genes: new insights into the role of oestrogen. *Cell Mol Life Sci* 2007; 64:1009–1032.
  34. Hambrock HO, Nitsche DP, Hansen U, Bruckner P, Paulsson M, Maurer P, Hartmann U. SC1/hevin. An extracellular calcium-modulated protein that binds collagen I. *J Biol Chem* 2003; 278:11351–11358.
  35. Sullivan MM, Puolakkainen PA, Barker TH, Funk SE, Sage EH. Altered tissue repair in hevin-null mice: inhibition of fibroblast migration by a matricellular SPARC homolog. *Wound Repair Regen* 2008; 16:310–319.
  36. Claeskens A, Ongenaes N, Neefs JM, Cheyngs P, Kaijen P, Cools M, Kutoh E. Hevin is downregulated in many cancers and is a negative regulator of cell growth and proliferation. *Br J Cancer* 2000; 82:1123–1130.
  37. Taylor AH, Abbas MS, Habiba MA, Konje JC. Histochemical evaluation of cannabinoid receptor and anandamide modulating enzyme expression in the human endometrium throughout the menstrual cycle. *Histochem Cell Biol* 2010; 133:557–565.
  38. Maccarrone M, Bari M, Di Rienzo M, Finazzi-Agro A, Rossi A. Progesterone activates fatty acid amide hydrolase (FAAH) promoter in human T lymphocytes through the transcription factor Ikaros. Evidence for a synergistic effect of leptin. *J Biol Chem* 2003; 278:32726–32732.
  39. Levy-Litan V, Hershkovitz E, Avizov L, Leventhal N, Bercovich D, Chalifa-Caspi V, Manor E, Buriakovsky S, Hadad Y, Goding J, Parvari R. Autosomal-recessive hypophosphatemic rickets is associated with inactivation mutation in the ENPP1 gene. *Am J Hum Genet* 2010; 86: 273–278.
  40. Okada H, Nakajima T, Yoshimura T, Yasuda K, Kanzaki H. Microarray analysis of genes controlled by progesterone in human endometrial stromal cells in vitro. *Gynecol Endocrinol* 2003; 17:271–280.
  41. Velarde MC, Aghajanova L, Nezhat CR, Giudice LC. Increased mitogen-activated protein kinase/extracellularly regulated kinase activity in human endometrial stromal fibroblasts of women with endometriosis reduces 3',5'-cyclic adenosine 5'-monophosphate inhibition of cyclin D1. *Endocrinology* 2009; 150:4701–4712.
  42. Gooz M, Gooz P, Luttrell LM, Raymond JR. 5-HT2A receptor induces ERK phosphorylation and proliferation through ADAM-17 tumor necrosis factor-alpha-converting enzyme (TACE) activation and heparin-bound epidermal growth factor-like growth factor (HB-EGF) shedding in mesangial cells. *J Biol Chem* 2006; 281:21004–21012.
  43. Jessmon P, Kilburn BA, Romero R, Leach RE, Armant DR. Function-specific intracellular signaling pathways downstream of heparin-binding EGF-like growth factor utilized by human trophoblasts. *Biol Reprod* 2010; 82:921–929.
  44. Shin HS, Lee HJ, Nishida M, Lee MS, Tamura R, Yamashita S, Matsuzawa Y, Lee IK, Koh GY. Betacellulin and amphiregulin induce upregulation of cyclin D1 and DNA synthesis activity through differential signaling pathways in vascular smooth muscle cells. *Circ Res* 2003; 93: 302–310.
  45. Tokushige N, Markham R, Russell P, Fraser IS. Different types of small nerve fibers in eutopic endometrium and myometrium in women with endometriosis. *Fertil Steril* 2007; 88:795–803.
  46. Chung J, Uchida E, Grammer TC, Blenis J. STAT3 serine phosphorylation by ERK-dependent and -independent pathways negatively modulates its tyrosine phosphorylation. *Mol Cell Biol* 1997; 17:6508–6516.
  47. Medina MG, Lebovic DI. Endometriosis-associated nerve fibers and pain. *Acta Obstet Gynecol Scand* 2009; 88:968–975.